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LIFE CYCLE ENVIRONMENTAL IMPACT OF MAGNESIUM AUTOMOTIVE COMPONENTS

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Abstract

The development of magnesium applications for automotive industries is receiving significant attention. One aspect of this attention is the consideration of the cradle-to-grave environmental impact of magnesium components. In order to be able to address this issue properly a life cycle assessment (LCA) needs to be carried out.

This paper reports on such an assessment for an automotive component, namely converter housing. The study investigates detailed impact starting from the production of magnesium ingots to the manufacture and assembly, use and recycling.

Extensive sensitivity analysis is conducted to examine the impact of key process parameters that can improve the environmental performance of the component. The parameters considered are: cover gases other than SF_6, improvements to product yield and use of secondary magnesium. From this analysis, a number of environmental performance scenarios are proposed and used to compare the impact of similar functional components made using of magnesium produced in China, aluminium and iron.

The investigations clearly show a significant reduction in the greenhouse gas impact may be achieved from the lighter weight of the magnesium components. Also, process improvements to reduce the impact improve the break-even distances in the use of automobiles at which magnesium becomes comparable with other competing metals.

Introduction

The environmental drive towards reducing emissions from automobiles has resulted in the growing use of lightweight magnesium components to achieve weight reduction. This drive calls for a clear understanding of the environmental impacts associated with the light-metal value chain. With a focus on this important domain, this paper addresses the greenhouse impact associated with manufacturing, using and recycling magnesium automotive components, and discusses some issues for improving the environmental performance of the value chain.

The life cycle stages of magnesium components broadly includes production of magnesium alloy from ore, manufacture of a representative magnesium component, assembly, use of automobiles, and recycling of the end of life vehicles (ELV) that are discarded after use. Many researchers have paid attention [1,2] to quantify the greenhouse impact of producing magnesium metal by electrolytic means. However, environmental issues related to manufacturing of components, and the advantages to be gained from using manufactured magnesium components in automobiles, have received only limited attention. In this paper, we have made an attempt to improve our understanding of the cradle to grave environmental impact by adding the manufacturing, use and recycling stages so as to extend the life cycle boundary from cradle-to-grave.

We use life cycle assessment (LCA) that is currently being recommended by international standards [3] to quantify the environmental impacts associated with a product, namely converter housing (CH). Using the results of the “cradle-to-grave” life cycle study, we have conducted sensitivity analysis on selected parameters that represent options for reducing GHG emissions. The parameters considered include reduction in energy use, improvements to product yield, increasing the use of secondary magnesium and light-weighting. The analysis is extended to compare the GHG emissions of using magnesium with other competing metals, such as iron and aluminium.

Goal and Scope of the Life Cycle Study

The principal goal of the current LCA study is assessment of different processes, materials, and systems that are major contributors to environmental impact through whole life cycle of magnesium automotive components and identification of possible improvements with the aim to reduce such impacts. The impact category that has been selected to address the above goal is the global warming impact that deals with the emission of greenhouse gases (GHG) from the product system.

In order to understand the impact of magnesium components that could be used in automobiles we have chosen for the LCA study a converter housing made from magnesium alloy AZ91, which houses the torque converter used in cars with automatic transmission (see Figure 1, also, the mass of the magnesium converter housing of 3.1kg is obtained from [4]).

The functional unit of this product is chosen to be the product itself, i.e. CH. The life cycle impact of a chosen magnesium component is therefore expressed in terms of impact units per component, and any comparison of the impact for magnesium with the impact of another material is made on the basis of the impact of the functional component (e.g. kg CO-eq/Mg CH vs. kg CO-eq/Al CH).

The life cycle product system for magnesium relevant to automotive applications may be viewed as a generic product

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system that is a collection of the four life cycle stages shown in Figure 2: Primary magnesium production, Manufacturing and assembly of components into vehicles, Use of vehicles, and finally, Secondary magnesium production by open loop recycling.

Each life cycle stage in the generic product system consists of several unit processes. The details of the processes that are used for making the component are described below.

Figure 1. Converter housing (CH)

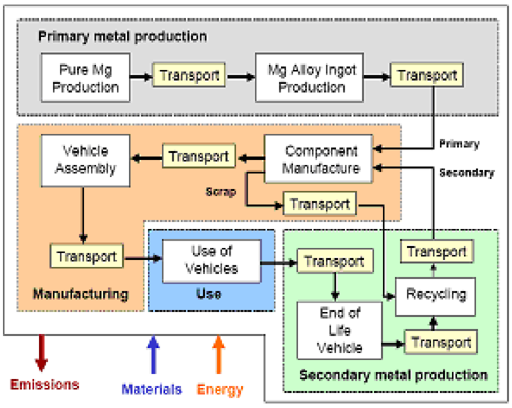

Figure 2. Generic product system considered for LCA study

Description of Processes in Product Systems

Primary Magnesium Ingot Production

This stage deals with the production of ingots of magnesium alloys from raw materials. We have considered production of magnesium alloy ingots in Australia by an electrolytic process [5] by using AMC proprietary technologies.

The process stages related to the production of magnesium alloy ingots in the generic product system (Figure 2) includes mining of ore, all the processes that are used for making pure magnesium, and the processes for making ingots of magnesium alloys from pure magnesium. The details of the various processes associated with the production of magnesium alloy ingots made by two different production routes have been presented in [6].

Manufacturing and Assembly of Converter Housing

Magnesium alloy ingots (both primary and secondary) are transported to component manufacturing, where alloy ingots are transformed into components for use in cars. The components are transported to vehicle assembly plants, where they may be further processed and assembled into cars. It is assumed that a cover gas that contains sulphur hexafluoride (SF_6) is used in the manufacturing plant for protecting molten magnesium form oxidation. All manufacturing scrap is recycled externally, i.e. magnesium scrap from manufacturing plants is transported to recycling centre, where secondary magnesium is produced.

The core manufacturing process that is used for manufacturing the magnesium converter housing is the HPDC process. (Figure 3 shows the product system associated with the manufacturing of magnesium CH). From the mass flow of magnesium shown in the figure, it may be seen that an amount of 5.709kg of magnesium alloy ingots is required to produce a converter housing of mass 3.1kg. It is assumed that the metal received by the manufacturing plant is made up of 70% of primary metal and 30% of secondary metal [7]. Further, the processes and electrical energy source are assigned to the currently adopted HPDC technology in USA for similar magnesium products and average electrical energy source in USA, respectively.

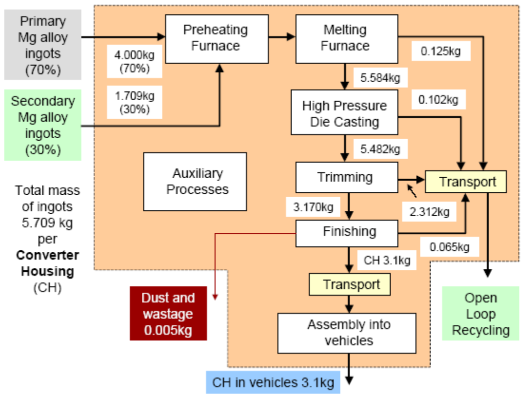

Figure 3. Manufacturing and assembly of CH

The various processes used in manufacturing magnesium converter housings and assembling them into vehicles (Figure 3) are described below.

Preheating and melting magnesium ingots. Ingots of magnesium alloy received by the die-casting plant are initially preheated to a temperature of 180°C using an electrical furnace, similar to patented “Ferrywheel” furnace [8], having a thermal efficiency of 50%.

The preheated magnesium alloy ingots are charged into melting furnace, which is located at the die-casting machine while casting magnesium. We have assumed that the melting furnace used in manufacturing is similar to the Rausch MM550 that consumes 1.3MJ of electrical energy per 1kg of magnesium melt [8] with a thermal efficiency of 62%. For calculating the GHG impact of consuming electrical energy in the die-casting operation, we have assumed an emission factor of 0.207 kg CO-eq/MJ of electrical energy on the basis of the average values including grid loss for producing electrical energy in the USA [9].

SF_6 cover gas is used while handling molten magnesium to prevent the oxidation of the metal. An average consumption of 0.96g of SF_6 per 1kg of molten metal is assumed. Approximately 10% of the SF_6 supplied is absorbed by molten magnesium.

Die-casting, trimming and finishing processes. Molten metal from the melting and holding furnace is transferred to the shot sleeve of the HPDC machine to produce the raw casting. We have used process data that are typical to the manufacturing of die-cast automotive components in the USA in estimating the materials and energy input for making the converter housing.

The output of die-casting machine contains the final desired product (3.1kg of CH) and additional solidified metal (2.482kg) in the runners and gates. The excess material is trimmed using a trimming machine, and sent to recycling centres for secondary metal production.

Auxiliary processes. There are many auxiliary and subsidiary processes that support the core processes in a die-casting plant. These include processes, such as systems that provide compressed air, plant for treating water, and others that form the essential infrastructure. These processes consume energy and use many materials and physical products, such as process consumables, clothing etc.

Assembly of converter housings into vehicles. The converter housings manufactured at the component manufacturing plant are transported to vehicle assembly plants, where they are assembled into vehicles. It is assumed that the transportation of converter housings is carried out using 40-ton diesel trucks over an average distance of 300kms.

Table 1 gives the process data used for the LCA study.

Secondary metal production

In this study, secondary magnesium production is treated as open-loop recycling, as shown in the generic product system (Figure 4). The open loop recycling stage involves transporting, shredding and melting of scrap; cleaning and alloying of the melt material; and casting molten metal as ingots.

The production of secondary magnesium by recycling assumes the current practice of magnesium recycling industry in the USA. New scrap sent from component manufacturing plants (about 60% of all scrap), and old scrap received from recycled cans (mostly) and other magnesium containing products (such as end of life of vehicles), are used by recyclers to produce secondary magnesium alloy ingots that meet the quality standards of manufacturers [7].

The operations associated with secondary magnesium production include (shown in Figure 4): recovery, preparation and handling of process materials; shredding and de-coating activities. The shredded scrap is then melted in a furnace. After melting, the melt is cleaned by adding flux. Then it is transferred to a holding furnace over a launder. Alloying takes place in the holding furnace.

Converter Housing: Manufacturing & Assembly

Process	Main materials (kg/CH)	Principal products (kg/CH)	Energy input (MJ/CH)
Preheating and melting magnesium ingots	Mg ingots 5.709 (Primary: 4.000; Second.: 1.709)	Molten Mg alloy: 5.584	El. energy: 1.92 + 7.42 (melting & holding)
	Cover gas SF6: 0.00549 dry air: 0.0608		
Casting, trimming and finishing	Molten Mg alloy: 5.584	Converter housing: 3.1	El. energy: 8.52
	Water: 7.5		
	Aluminium shot: 0.0002		
	Lubricant: 0.013		
Auxiliary processes	Cotton, rubber, Fellpro, etc.		El. energy: 3.2 + Thermal energy: 17.73 (gas and fuel)
	Water from all processes: 6.9		
Trans-tion to assembly plant	Diesel: 0.054		Energy from diesel fuel: 2.28
Assembly into car			El. energy: 1.51

Table 1. Details of processes for manufacturing CH

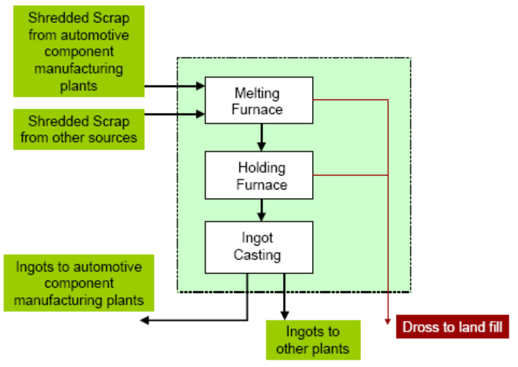

Figure 4 Open loop recycle of magnesium scrap for secondary metal production

On the basis of the assumption that the ratio of primary to secondary magnesium ingots received is 70:30%, the mass of secondary magnesium ingots delivered to the manufacturing plant is 1.709kg for making a converter housing of mass 3.1kg. Details of energy and material consumption in secondary magnesium production are given in Table 2.

Use in cars.

During use phase, the fuel consumption (and hence the emission) is assigned to the components on basis of the mass contribution to the whole mass of the car. A mid-size car (with a mass $\mathbf{M_V}$ = 1400kg and fuel consumption of $\mathbf{K}$ = 8.5 litres per 100km of driving [10]) is considered for the study, and it is assumed that the car reaches the end of its life after a driving distance of 200,000kms. Assuming that the average fuel consumption to be linearly dependent on the mass of the car, the amount of fuel consumed over the life of the car in moving 1kg of the magnesium component used is given by,

Converter housing: open loop recycling

Process	Materials input (kg/CH)	Principal products (kg/CH)	Energy input (MJ/CH)	Comments
Recycling Mg (open-loop)	Mg scrap: (2.312+1.16) x 0.55 Fluxes: 0.515 SF6:	Mg alloy ingots: 1.709 (for CH) 1.36 (for other products)	El. Energy: 6.48 Nat. gas: 4.16	Energy and materials allocated for CH. Dross and sludge to landfill:0.65

Table 2. Details of open-loop recycling for CH

$$F = K \times L / M_V = (8.5/100) \times 200000 / 1400 =$$
$$=12.14 \text{ litres of fuel/kg of component.}$$

Using the data for GHG emission from cars of 2.85 kg CO2 eq/litre [10], we get the life cycle GHG emission from using a component be 34.60 kg CO-eq/kg of component.

In calculating the GHG emission resulting from the use of a component in a car, we have accounted for the mass of the support structure that carries the component in the car. According to [11, 12] this secondary weight can save up to 50% of the primary weight save, though we have made a conservative assumption of 25%. Table 3 gives details of using the converter housing in a car.

Converter Housing: use in cars

Process	Materials input (kg/kg of product)	Energy input (MJ/kg of product)	Comments
Use CH in car	Petrol: 34.14kg for 200,000km	Energy from petrol: 1623.2MJ	Mass of replacement Mg: 3.1 X 1.25 kg

Table 3. Details of using converter CH in car.

Life Cycle GHG Emission Impact of Converter Housing

A life cycle model was created for the product system shown in Figure 2 using SimaPro LCA software [11]. The model was analysed to estimate life cycle GHG emission inventories and global warming impacts for different scenarios for the various processes that make up the product system. In estimating the global warming impact, the global warming potentials (GWP) of the various greenhouse gases emitted were used to quantify the impact in terms of kg CO-eq /kg of the functional unit under consideration. Aggregated global warming impacts for the generic processing stages were obtained as a result of the study.

The basic model has been considered to quantify the life cycle impact under nominal conditions. The basic system is characterised by the following: Primary magnesium alloy ingots are produced in Australia using the AM process, and transported to the USA. (AM-cover is used as a cover gas while casting ingots). Secondary magnesium alloy ingots are produced in the USA using the scrap produced in the USA. (SF_6 is used as a cover gas while casting secondary ingots). Manufacturing of converter housings is done in the USA using a mix of 70% primary magnesium (from Australia) and 30% secondary magnesium (from the USA). The converter housings are assembled into vehicles in the USA. The car with the manufactured converter housing is used in the USA over a total driving distance of 200,000kms Impacts under conditions that deviate from the nominal condition are assessed in sensitivity analyses.

Figures 5 and 6 present the GHG impact and the primary energy consumption of the converter housing under nominal system conditions, respectively. The overall “cradle-to-grave” life cycle GHG impact for the CH is 349.8 kg CO2-eq/CH. It can be seen (Figure 5) that the primary production, manufacturing and use stages of the life cycle contribute significantly towards the GHG impact.

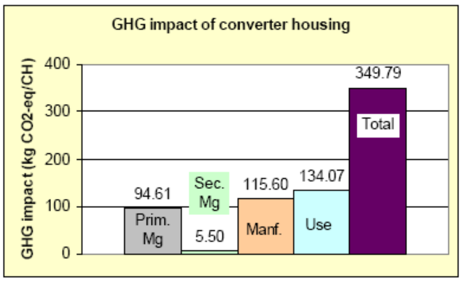

Figure 5. GHG impact of CH over the life cycle.

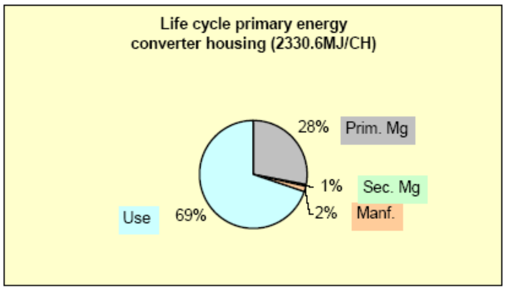

Figure 6. Primary energy consumption of CH over the life cycle

The primary energy over the life cycle of the CH is 2330.6MJ/CH, of which most of the contribution is from the primary magnesium production and use stages. The manufacturing stage uses little primary energy. The enhanced GHG impact of manufacturing is primarily due to the use of SF_6, which has a very high GWP of 22,200.

Sensitivity analysis of the impact of converter housing

The sensitivity analysis of the life cycle environmental impact of the CH has been conducted for the following important factors: usage of cover gas in manufacturing and recycling stages, product yield in manufacturing stage, source of primary magnesium alloy ingots and the proportion of secondary metal used by the product system. The calculated results are shown in Figures 7 and 8. It can be seen that the GHG impact is significantly reduced by the use of AM-Cover gas for manufacturing and recycling as the gas contains HFC-134a having a GWP of 1,600. Significant reductions in the GHG impact can also be achieved by increasing the product yield in manufacturing from the nominal value of 54%, and also by increasing the proportion of secondary magnesium used for manufacturing from the nominal value of 30%.

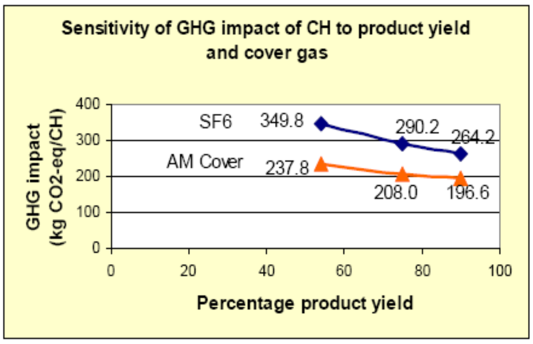

Figure 7. Sensitivity of GHG impact of CH to product yield and the cover gas used in manufacturing and recycling

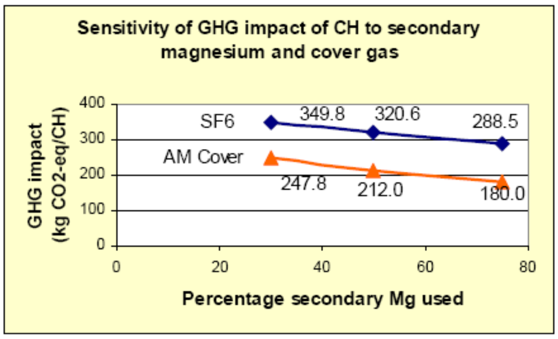

Figure 8. Sensitivity of GHG impact of CH to product percentage of secondary magnesium and the cover gas used in manufacturing and recycling

Discussion of Results

Cover Gas: The results of the study clearly show that the use of a cover gas that contains SF_6 (GWP: 22,200) to protect molten magnesium in the manufacturing and recycling stages of the magnesium life cycle produces a high GHG impact. The AM-Cover gas that contains HFC-134a (GWP: 1,600) has a significant influence in reducing the GHG impact of magnesium products.

Product yield in manufacturing: The product yield obtained in the high-pressure die-casting operation used for manufacturing products such as the CH is as low as 55%. This results in not only a higher GHG impact, but also a large amount of scrap that needs to be sent out the manufacturing plant for recycling. It is essential that the product yield from die-casting operations is increased to reduce the GHG impact of magnesium.

Secondary metal content: We have assumed in this study that the secondary magnesium ingots obtained from recycling constitute 30% of the total magnesium ingots used for manufacturing magnesium components. If this is increased to 75%, the GHG impact over the life cycle of magnesium could be reduced by as much as 25% from the nominal impact calculated in the study. One must note that in-house recycling of scarp can further reduce the GHG impact of secondary magnesium, such as through savings in transport and sorting.

Light weighting cars: The study also highlights the emission reduction in the use stage of a light-weighted passenger car that is built with magnesium components. To illustrate the comparative performance of magnesium, we have compared the impact of nominal product system with the impacts of five other competitive materials product systems, as shown in Table 4.

#	Product System	Primary	Second	Manuf.	Cover Gas	Ref..
1	Nominal	AU. Mg 70%	Open-loop US 30%	US	SF6	This study
2	China Mg	China Mg 70%	Open-loop US 30%	US	SF6	This study, [14]
3	Iron	AU 50%	AU. 50%	AU.	N/A	[9]
4	AU. Al	AU. Al 70%	AU. AL 30%	AU.	N/A	[9,16]
5	US Al	US Al.40%	USA Al.60%	US	N/A	[9,13]
6	AU. Mg & AM-Cover	AU. Mg 70%	Open-loop US 30%	US	AM-Cover	This study

Table 4. Product systems considered for comparison impacts

The GHG impacts of the above six product systems are compared in Figure 9. The impact values shown in this figure assume a life cycle total driving a distance of 200,000kms. It can be seen from this figure that the largest GHG impact of the CH results from the Chinese magnesium product system (product system 2) that uses SF_6 as the cover gas for both manufacturing and recycling stages. The nominal system (product system 1) that is based on Australian magnesium and uses SF_6 gives the second highest GHG impact. A much lower impact results (product system 6) if AM-Cover gas is used instead of SF_6 with Australian magnesium. The lowest impact is produced by CH made from US aluminium due to high recycling ratio (60% of secondary aluminium).

Figure 10 gives the GHG impact of the six product systems as a function of the driving distance. This figure provides information on the break-even driving distance. In the case of the product system 6 that uses Australian magnesium and AM-Cover breaks even with the CH made from iron (product system 3) at a driving distance of ~ 100,000kms. This means that CH made from 70% Australian magnesium using AM-Cover gas for secondary magnesium production as well as for manufacturing has a lower GHG impact than that of an iron-based CH when the driving distance exceeds 100,000kms. Also, it may be seen from Figure 10 that such a converter housing will be only as good as converter housing made from Australian aluminium.

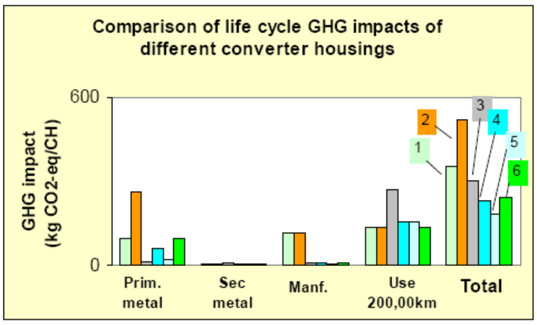

Figure 9. Comparison of GHG impact of different materials product systems
1 – Nominal; 2 – Chinese Mg; 3 – Iron; 4 – AU Al; 5 – US Al; 6 – AU Mg and AM-cover

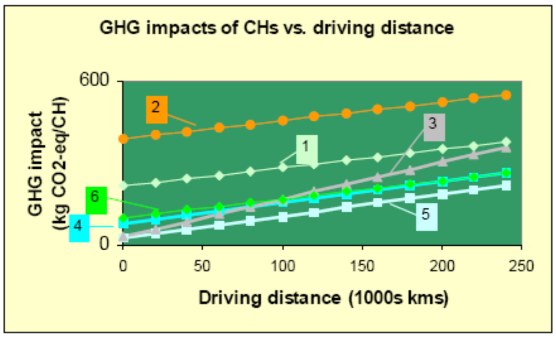

Figure 10. GHG impact of different product system for CH vs. driving distance
1 – Nominal; 2 – Chinese Mg; 3 – Iron; 4 – AU Al; 5 – US Al; 6 – AU Mg and AM-cover

Conclusions

In the conducted study we have estimated the GHG impacts over the entire life cycle of magnesium CH made from Australian magnesium.

The study clearly shows that the use stage of a passenger car contributes significantly to the total GHG impact of magnesium components over their entire life cycle. A significant reduction in the GHG impact during the use stage, and hence over the entire life cycle, may be achieved from a significant mass reduction of a car by using magnesium components. The magnesium CH can only provide improvement if SF_6 will be substituted by other cover gases with significantly lower GWP.

Sensitivity analyses conducted clearly indicate the reduction in GHG impact when AM-Cover gas, instead of SF_6, for protecting molten magnesium from oxidation during the manufacturing and secondary metal production stages is used. Higher percentage use of secondary magnesium and increase of yield in die-casting have substantial reductions as well.

This study has dealt only with the GHG impact of magnesium components, and comparisons with other metals are based on the GHG impact too. However, other impact categories need to be considered if magnesium components are to be compared with components made from non-metallic materials.

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